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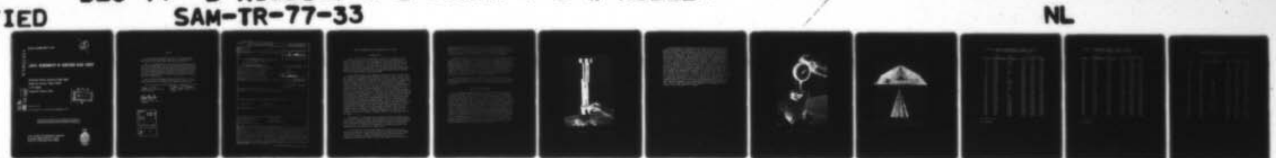

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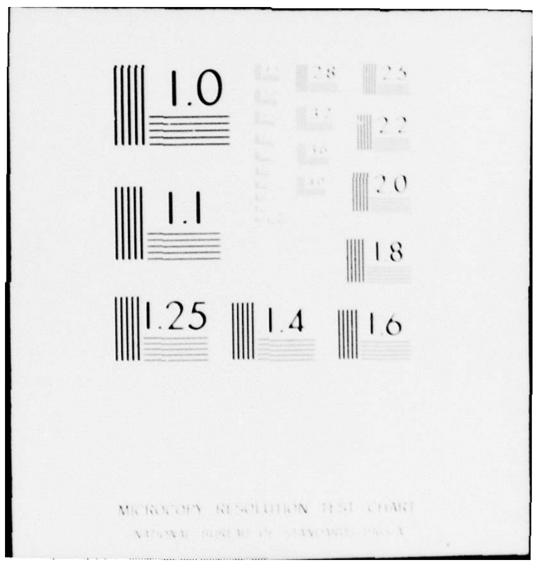
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IMPACT VULNERABILITY OF SCRATCHED GLASS LENSES

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USAF SCHOOL OF AEROSPACE MEDICINE
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Ophthalmic glass lenses of dress thickness were diamond scribed on their convex surfaces after heat or chemical tempering to a significant penetration of their compression layer. Nontempered lenses were similarly scratched. All were subjected to dropball impacts to examine whether the damaged tempered lenses would be more vulnerable to breakage than the scribed lenses that were not under internal stress. The results showed that the nontempered lenses had less impact resistance than the tempered. No significant difference in impact resistance was seen between the chemical- and heat-tempered groups.

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IMPACT VULNERABILITY OF SCRATCHED GLASS LENSES

INTRODUCTION

Since early 1972 all conventional spectacles dispensed in the United States by prescription or over the counter are required to be "impact resistant" (4). This requirement is satisfied by testing the lenses to the impact of a 1.59-cm (5/8-in) steel ball falling from a height of 127 cm (50 in) onto the convex surfaces while resting on a neoprene gasket and standard base (1). To insure survival, glass lenses subjected to this test are heat or chemically tempered and as blemish free as the manufacturers can produce them.

Heat-tempered lenses are produced by oven heating to near melt and then rapidly air quenching both surfaces by blower. Clear, crown lenses are chemically tempered by insertion into a hot potassium chloride salt bath where over a period of time sodium ions in the lens are displaced by larger potassium ions from the bath. In both processes outer-band layers of compression are formed in the lens which are counterbalanced by a central core under tension. The depth of the compression layer in the thermal-treated lens is approximately 1/5 to 1/4 the thickness of the lens, or 0.44 to 0.55 mm for a 2.2-mm-thick lens; the chemical treatment results in a compression layer of about 0.06 to 0.11 mm in depth which is not related to lens thickness (5). Spontaneous breakage of heat-tempered, dress-thickness (approximately 2 mm) lenses has been reported (6), and this is believed to be due to the sudden release of tension associated with defects in the outer compression band. Park (7) indicated that since chemical strengthening induces higher stresses in substantially thinner compression layers, the internal tension of the lens is very low. He therefore would expect that when a deep scratch penetrates the compression layer or when the critical impact strength of the chemical-tempered lens is exceeded, "violent breakage is less likely to occur." Elmstrom (3) has stated that a chemical-tempered lens will lose its impact resistance if a scratch is deeper than the ion-exchange layer on the lens.

Silberstein (9) reported on the increased breakage susceptibility of heat-tempered safety lenses after extended wear where surface marring was evident. Reports by other investigators on testing surface-damaged heat- and chemical-tempered lenses of dress thickness have followed (2,7,8,10,11). All indicated a lessening of breakage resistance compared with results from factory fresh lenses.

In a University of California study (9), pinpoint air abrasion damage was generated on the front and rear surfaces of heat- and chemical-tempered lenses. Almost invisible pinpoint abrasion reduced the fracture resistance of chemically hardened lenses to the level of undamaged heat-tempered lenses, and the same abrasion level applied to

heat-treated lenses reduced their fracture resistance to that of non-damaged, untempered lenses. Scaief (8) analyzed the results of the University of California study and indicated that the pinning procedure is more detrimental to fracture resistance than surface-scratching procedures. How these technics were equated was not explained.

The glass spectacle lenses processed by large military laboratories are chemically treated, while those fabricated by smaller single-vision laboratories are thermally treated. There is no question concerning the superior impact resistance in dropball testing of unblemished treated lenses compared with that of nontreated lenses, with all other physical factors being the same. Curiosity on two counts preceded the infliction of deep scratches with lenses under stress due to heat or chemical tempering: 1) Would they survive the mechanical process of scratching; and if so, 2) Were they more susceptible to breakage from dropball impact than a nontempered lens similarly scratched?

This study was designed to compare the impact vulnerability of tempered and nontempered lenses that were subjected to a single, depth- and length-controlled scratch placed centrally on the convex surface of the lenses.

PROCEDURE AND FINDINGS

In an informal telephone survey, the median prescription power filled by military laboratories was determined to be -1.00-D sphere. All lenses used were this power, calipered approximately 2.2 mm thick, and the product of the same optical company. All were edged to 48 mm round, using AIT Mark V bevel edgers, and finished by hand on a ceramic wheel. Then 30 lenses were heat tempered on the Shuron Continental Lens Hardening Unit #495; 30 were processed on the Kirk Chemical Treatment Unit Model #1411; and 30 were not treated. Each lens, placed in a jig (Fig. 1) that permitted a diamond tip to arc across the convex lens surface, received a scratch 3.0 mm long and approximately 0.06 mm deep. A 4.4-kg (10-lb) weight provided a uniform pressure on the diamond to produce the scratches, and all lenses were oriented so the scribe went from left to right. The 3.0-mm scratch length was arbitrarily chosen; the 0.06-mm depth selection was based on compression-layer thickness usually associated with the chemically tempered lens. An air jet was used to remove glass debris from the scratch and lens surface. Not a single lens broke in the scratch-generation process.

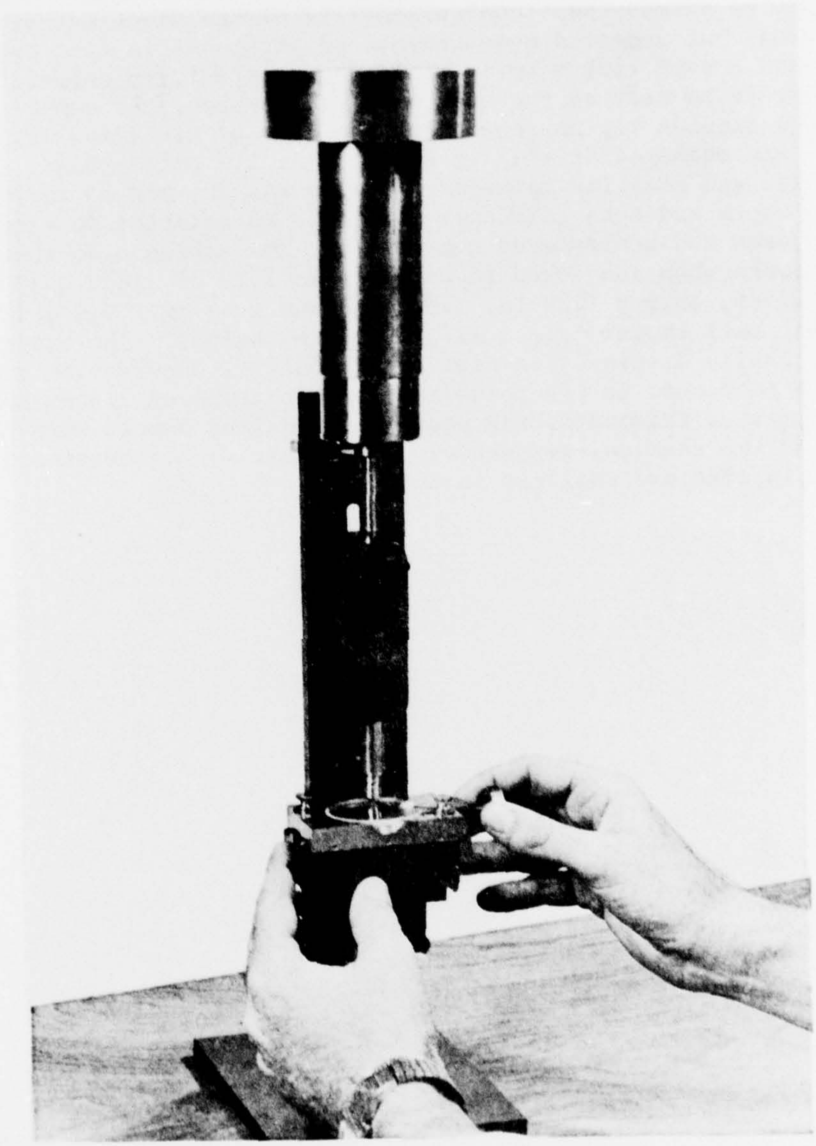

Figure 1. Jig diamond tip scribes for lens scratch.

Several methods for determining the depth of the scratch were considered: photographic, profilometry using laser-beam reflection, and a mechanical probe. The photographic and laser approaches were abandoned when curved surface and scratch-relationship difficulties arose and could not be surmounted. The reliability of the probe method was also questioned, but repeated measurements of scratches in flat ophthalmic lenses and curved test samples yielded consistent, repeatable results. To permit it to seat at the bottom of the scratch, the depth gauge (Fig. 2) used a carbide tip narrower than the diamond tip (Fig. 3). Each scratch was measured at the lip edge and at its bottom near its origin, centrally, and near its terminus. Tables 1A, 1B, and 1C indicate the scratch depth and lens thickness measurements relating to each lens in the tempered and nontempered categories. The tables also show which lenses broke when subjected in sequence to 1.59 cm, 16.2 g (5/8 in, 0.57 oz); 2.22 cm, 45.0 g (7/8 in, 1.59 oz); and 2.54 cm, 66.6 g (1 in, 2.35 oz) steel ball impact from a 127-cm (50 in) height. The breakage history is graphically displayed in Fig. 4. In general observation of the breakage patterns, it was noted that the nontempered lenses broke into small numerous fragments, the heat-tempered-lens debris were larger in size, and the chemical-tempered-lens segments were consistently the largest in size and smallest in number.

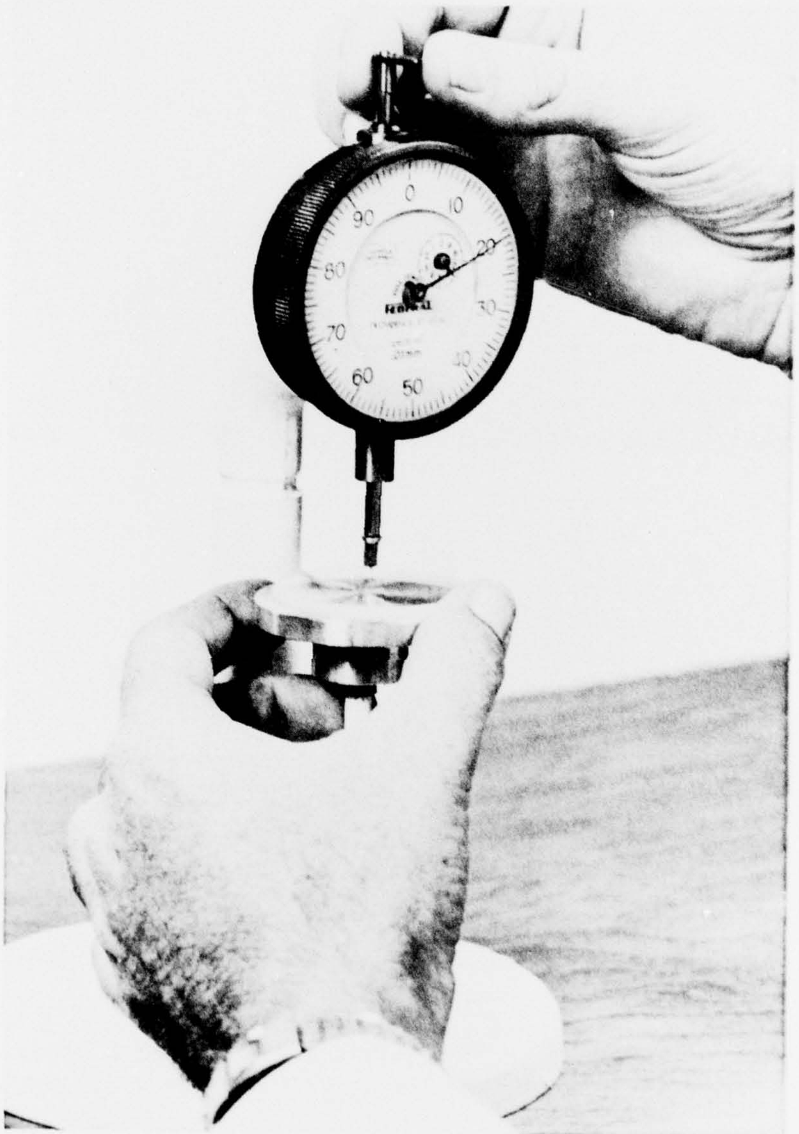

Figure 2. Scratch-depth gauge.

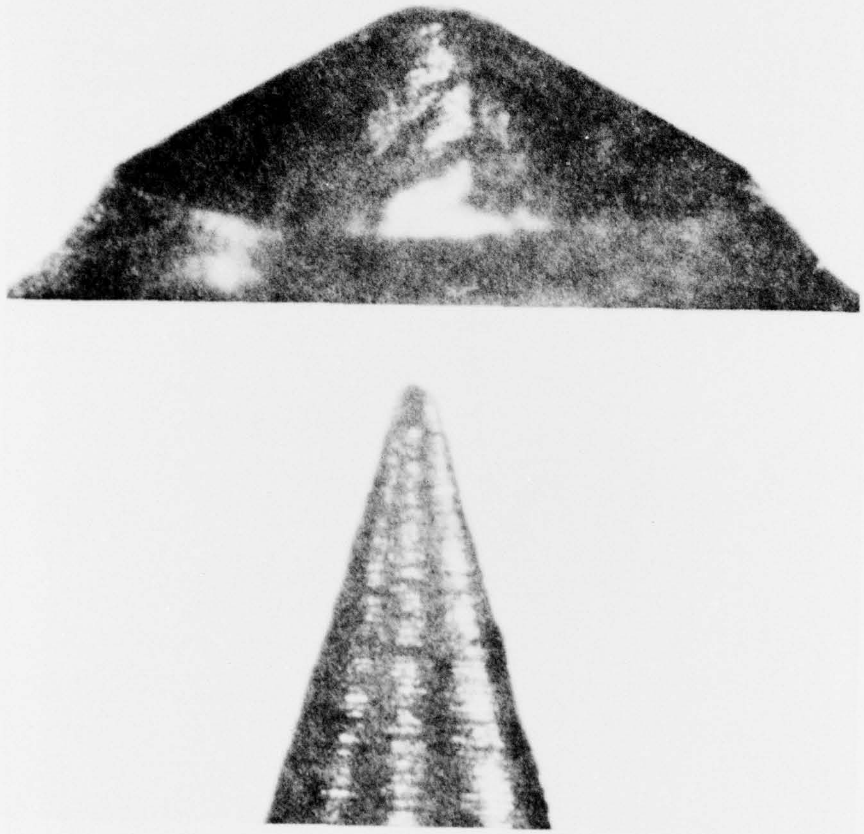

Figure 3. Upper: Diamond scriber used to scratch lenses;
Lower: Carbide tip used to measure scratch.

TABLE 1A. CHEMICAL-TEMPERED LENSES: THICKNESS, DROPBALL (FROM 127-cm) BREAKAGE, AND SCRATCH DEPTH

Lenses	Center thickness (mm)	Ball size (cm)*	Scratch depth (mm) Left	Center	Right
1.	2.18	2.54	0.105	0.06	0.015
2.	2.15	2.22	0.105	0.05	0.01
3.	2.12	1.59	0.115	0.07	0.04
4.	2.28	0	0.01	0.005	0.01
5.	2.18	0	0.015	0.005	0.00
6.	2.12	1.59	0.05	0.06	0.04
7.	2.25	2.22	0.03	0.02	0.005
8.	2.15	0	0.11	0.06	0.005
9.	2.17	0	0.06	0.07	0.06
10.	2.15	0	0.065	0.03	0.015
11.	2.18	1.59	0.11	0.055	0.07
12.	2.17	1.59	0.055	0.04	0.01
13.	2.1	1.59	0.06	0.065	0.01
14.	2.1	0	0.06	0.05	0.02
15.	2.19	1.59	0.05	0.04	0.04
16.	2.12	2.54	0.07	0.01	0.01
17.	2.2	0	0.06	0.005	0.01
18.	2.17	0	0.14	0.035	0.02
19.	2.2	2.22	0.075	0.06	0.045
20.	2.19	0	0.01	0.02	0.02
21.	2.18	2.22	0.10	0.115	0.04
22.	2.15	2.22	0.065	0.045	0.025
23.	2.12	2.22	0.01	0.00	0.00
24.	2.1	2.54	0.08	0.035	0.04
25.	2.2	2.54	0.035	0.065	0.015
26.	2.18	1.59	0.02	0.08	0.01
27.	2.19	1.59	0.075	0.005	0.005
28.	2.2	1.59	0.065	0.045	0.015
29.	2.2	2.54	0.01	0.02	0.015
30.	2.1	2.54	0.045	0.045	0.02

*0 - Survived

TABLE 1B. HEAT-TEMPERED LENSES: THICKNESS, DROPBALL (FROM 127-cm) BREAKAGE, AND SCRATCH DEPTH

Lenses	Center thickness (mm)	Ball size (cm)*	Scratch depth (mm) Left	Center	Right
31.	2.2	1.59	0.03	0.04	0.03
32.	2.2	2.22	0.03	0.045	0.04
33.	2.25	1.59	0.04	0.045	0.03
34.	2.25	2.22	0.04	0.045	0.035
35.	2.15	2.54	0.045	0.04	0.025
36.	2.28	1.59	0.03	0.0325	0.02
37.	2.2	0	0.055	0.035	0.035
38.	2.18	1.59	0.045	0.025	0.045
39.	2.15	2.54	0.04	0.035	0.045
40.	2.09	2.22	0.045	0.055	0.045
41.	2.2	1.59	0.05	0.05	0.04
42.	2.15	0	0.05	0.035	0.07
43.	2.2	1.59	0.04	0.0425	0.03
44.	2.22	1.59	0.04	0.04	0.035
45.	2.2	2.22	0.05	0.04	0.045
46.	2.2	1.59	0.025	0.03	0.05
47.	2.1	1.59	0.060	0.045	0.055
48.	2.15	1.59	0.045	0.04	0.045
49.	2.17	2.22	0.04	0.06	0.045
50.	2.22	2.54	0.05	0.04	0.05
51.	2.18	1.59	0.05	0.05	0.035
52.	2.12	2.54	0.05	0.045	0.045
53.	2.1	2.54	0.05	0.035	0.04
54.	2.19	2.22	0.06	0.03	0.065
55.	2.12	0	0.035	0.040	0.06
56.	2.26	2.54	0.035	0.06	0.04
57.	2.15	1.59	0.045	0.035	0.035
58.	2.1	1.59	0.03	0.04	0.03
59.	2.2	2.22	0.06	0.035	0.06
60.	2.25	2.22	0.04	0.04	0.055

*0 - Survived

TABLE 1C. NONTEMPERED LENSES: THICKNESS, DROPBALL (FROM 127-cm) BREAKAGE, AND SCRATCH DEPTH

Lenses	Center thickness (mm)	Ball size (cm)	Scratch depth (mm) Left	Scratch depth (mm) Center	Scratch depth (mm) Right
61.	2.25	1.59	0.05	0.04	0.065
62.	2.3		0.11	0.055	0.050
63.	2.1		0.055	0.065	0.045
64.	2.28		0.095	0.07	0.04
65.	2.18		0.07	0.075	0.065
66.	2.18		0.055	0.075	0.06
67.	2.12		0.06	0.08	0.025
68.	2.22		0.07	0.05	0.045
69.	2.25		0.08	0.07	0.05
70.	2.22	(All broke at 1.59-cm-ball impact)	0.045	0.055	0.04
71.	2.2		0.03	0.05	0.05
72.	2.3		0.05	0.05	0.055
73.	2.29		0.05	0.06	0.055
74.	2.23		0.075	0.065	0.05
75.	2.25		0.08	0.06	0.085
76.	2.18		0.065	0.08	0.065
77.	2.3		0.05	0.05	0.05
78.	2.3		0.03	0.065	0.05
79.	2.18		0.11	0.06	0.045
80.	2.18		0.04	0.07	0.045
81.	2.23		0.05	0.025	0.02
82.	2.12		0.055	0.045	0.045
83.	2.3		0.05	0.05	0.06
84.	2.28		0.08	0.065	0.05
85.	2.21		0.06	0.07	0.04
86.	2.25		0.04	0.03	0.045
87.	2.18		0.07	0.045	0.065
88.	2.1		0.055	0.06	0.065
89.	2.22		0.05	0.05	0.035
90.	2.1		0.04	0.04	0.045

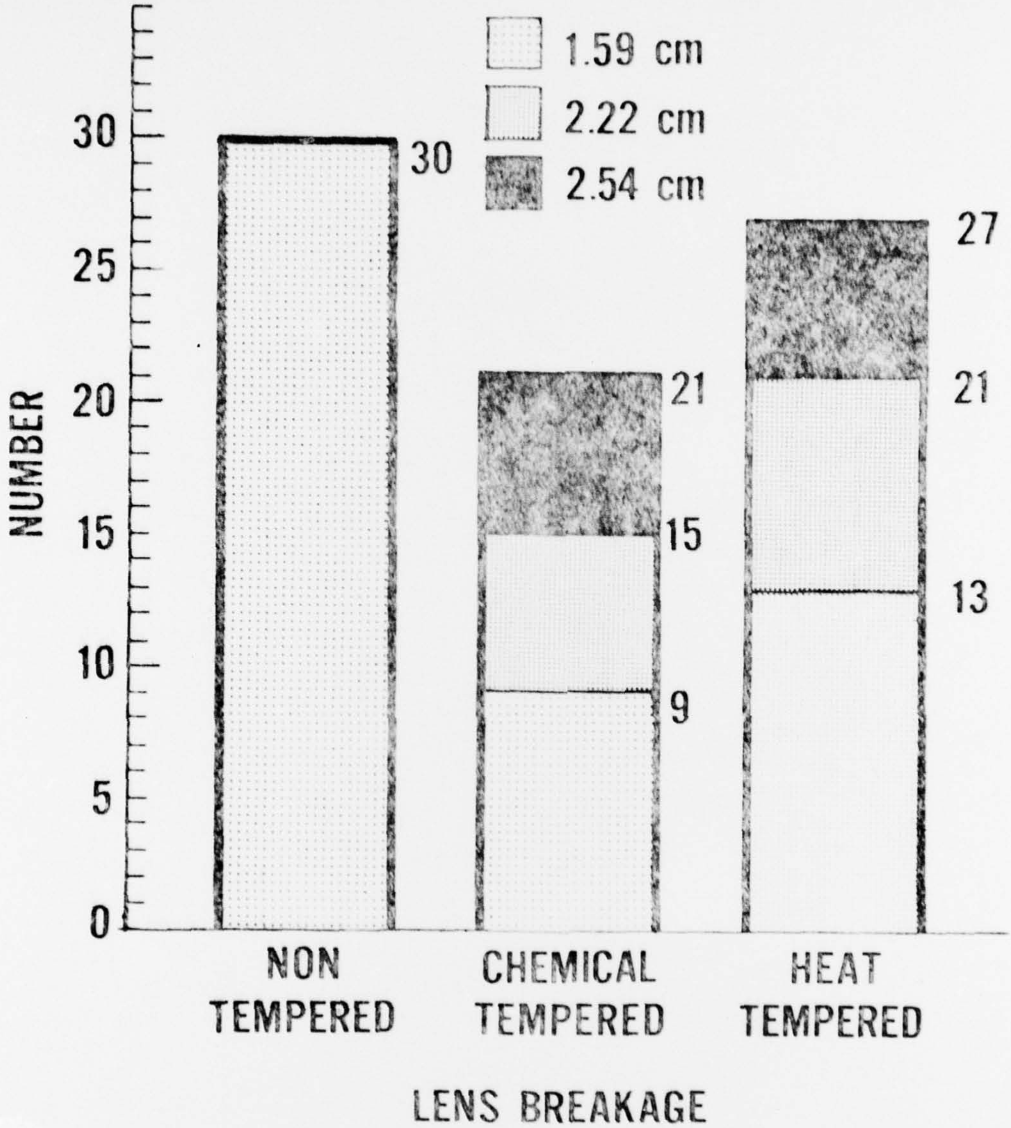

Figure 4. Lens breakage at steel-ball (1.59-, 2.22-, and 2.54-cm) impact from 127-cm height.

Table 2 provides thickness comparisons between the three groups of lenses; Table 3 relates the groups for scratch depths; and Table 4 compares the groups for dropball breakage.

TABLE 2. LENS THICKNESS (mm)

Lens Group	Median thickness	Minimal thickness	Maximal thickness
Nontempered	2.22	2.10	2.30
Heat tempered	2.20	2.09	2.28
Chemical-tempered	2.18	2.10	2.28

Statistical results (Wilcoxon's Rank Sum Test)

Comparison (P)	
Heat versus chemical	NS
Nontempered versus chemical	<.005
Nontempered versus heat	<.025

TABLE 3. SCRATCH DEPTH (mm)

	Left-end depth			Center depth			Right-end depth		
	Median	Min	Max	Median	Min	Max	Median	Min	Max
Lens Group									
Nontempered	.055	.030	.110	.060	.025	.080	.050	.020	.085
Heat-tempered	.045	.025	.060	.040	.025	.060	.040	.020	.070
Chemical-tempered	.063	.010	.140	.045	.000	.115	.015	.000	.070

Statistical results (Wilcoxon's Rank Sum Test)

Comparison (P)	Left end	Center	Right end
Heat versus chemical	<.005	NS	<.001
Nontempered versus chemical	NS	<.01	<.001
Nontempered versus heat	<.001	<.001	<.005

TABLE 4. DROPBALL TEST RESULTS

	1.59-cm ball			+ 2.22-cm ball		+ 2.54-cm ball	
Lens group	No. lenses	No. broken	% breakage	No. broken*	% breakage*	No. broken*	% breakage*
Nontempered	30	30	100	-	-	-	-
Heat-tempered	30	13	43	8(21)	27(70)	6(27)	20(90)
Chemical-tempered	30	9	30	6(15)	20(50)	6(21)	20(70)

Statistical results (Fisher's exact test)

Comparison	1.59-cm ball	+ 2.22-cm ball	+ 2.54-cm ball
Heat versus chemical	NS	NS	NS
Nontempered versus chemical	<.001	No test	No test
Nontempered versus heat	<.001	No test	No test

*(Accumulated total)

Wilcoxon's Rank Sum Tests were used to test for group differences with respect to lens thickness and scratch depth. While no statistical difference was found between the tempered groups, the nontempered lenses were significantly thicker than either set of tempered lenses. The scratch depth of the nontempered lenses was significantly greater than of the heat-tempered lenses at all three measurement locations, and in the center and right positions, also greater than of the chemical-tempered lenses. The tempered lenses differed from each other in depth at both ends of the scratch but showed no significant difference at the center. High-magnification photos of lenses in each group indicate the scratch surfaces are far from smooth in texture (Fig. 5). The chemical-tempered lens characteristically showed a gouge at the start of the scratch, probably the cause of the initial large depth reading.

The percents of breakage for lens groups were compared, using Fisher's Exact Test for 2 x 2 Contingency Tables. This was done for the 1.59-cm dropball data, then the combined 1.59- and 2.22-cm data, and finally, the combined data of all three drop tests. Only the 1.59-cm data applied to the nontempered-lens group since 100% breakage occurred with that size dropball.

In Table 4 the breakage of the nontempered lenses is seen to be significantly greater than of the tempered groups. No statistical difference is seen between the tempered groups for any of the dropball tests (1.59-cm, 1.59- + 2.22-cm, and 1.59- + 2.22- + 2.54-cm balls).

Figure 5. Characteristic scratch appearance; Upper: Chemical-tempered lens; Middle: Heat-tempered lens; Bottom: Nontempered lens.

In Tables 1A, 1B, and 1C it can be seen that the scratch depths generated by the 4.4-kg force vary between individual lenses and between the groups of lenses. The nontempered lenses demonstrated a 0.055-mm mean depth, and it was decided to compare their 1.59-cm-dropball breakage with that of the heat- and chemical-tempered lenses that had a scratch depth of 0.055 mm or more at any location. The 0.055-mm scratch depth was seen in 22 chemical-tempered lenses, and 8 of these succumbed (36%); of the 10 heat-tempered lenses with the 0.055-mm scratch depth, 1 broke under the 1.59-cm ball. Thus, the scratched tempered lenses showed more impact resistance than the nontempered. Insufficient sample numbers make statistical comparisons between the heat- and chemical-tempered lenses uncertain.

In comparing the treated groups in Table 4 on a numerical basis, breakage of the heat-tempered lens was greater in all categories than the chemical-tempered lens. It was decided that collecting additional data for a more powerful test for differences was warranted. Fifty additional lenses in each group were processed, scratched, and drop-balled one time with the 2.54-cm ball. Of the chemical-tempered lenses, 34 succumbed to the dropball; of the heat-tempered lenses, 33 succumbed. When these data were combined with the original, the breakage was found to be 68.8% (55/80) for the chemical-tempered group, and 73.8% (59/80) for the heat-tempered group. The difference in these percentages was not statistically significant.

DISCUSSION

The -1.00-D tempered spectacle lenses were no more vulnerable than nontempered lenses to breakage due to the mechanical stress of deep-scratch generation at the apex of the convex surface compression layer.

Also, the heat- and chemical-tempered glass lenses had higher survivability to dropball impact than the nontempered glass lenses comparably damaged. The scratch depths for the tempered lenses were equivalent, but the nontempered were scribed deeper than either the chemical- or heat-tempered lenses, with all factors kept constant. This indicates that tempering alters the physical characteristic of the glass surface, making it more resistant to scratching. When compared with the laboratory experience with nonscratched tempered lenses the impact vulnerability of heat-and chemical-tempered lenses to the standard dropball test is increased when the convex surface is deeply scratched. Even though the chemical-tempered lenses had scratches that penetrated through the compression layer, or nearly so, the impact vulnerability was not statistically different than for the heat-tempered lenses with compression layers 7 to 9 times as thick.

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